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AUTOMATED CROWN REPLICATION USING SOLID PHOTOGRAPHY[SM] (FINAL REPORT)

R. Schmidt
L. Waszak
R. Rongo
R. Segnini

October 1977

Supported by

U.S. ARMY MEDICAL RESEARCH AND DEVELOPMENT COMMAND
Washington, D.C. 20314

Contract No. DAMD 17-77-C-7041

Solid Photography Inc.
536 Broadhollow Road
Melville, N.Y. 11746

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A feasibility study applying Solid Photography, an optical, three-dimensional technology, to automatic replication of dental crowns out of inexpensive, non-strategic material. This study demonstrated that the interior and exterior surfaces of a dental crown pattern can be measured by Solid Photography to an accuracy on the order of ±0.002 inch. The interior surface was obtained by measuring the tooth post upon which the crown pattern was formed. A

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AUTOMATED CROWN REPLICATION USING SOLID PHOTOGRAPHY[SM]

SUMMARY

The purpose of this study contract was to determine if Solid Photography[SM] could be used to obtain a digital data base accurately enough to enable a numerically-controlled machine to cut dental crowns. Solid Photography is a new optical, three-dimensional measuring technology developed by Solid Photography, Inc. The object of automatically milling crowns instead of casting crowns, as is conventionally done, is to obviate the need for using costly strategic casting materials as well as to reduce the labor cost and time involved in producing crowns. Further, it was envisioned that other benefits would accrue by virtue of the fact that the Solid Photography technology inherently produces a three-dimensional digital data base that can be transmitted over conventional communications circuits and used by the many digital resources presently available.

A tooth post and wax crown pattern were supplied to Solid Photography Inc. to photograph and produce a digital data base describing the inner and outer crown surfaces to an accuracy on the order of ±0.002 inch. The data base was then used to program the cutting profile of a four-axis milling machine to directly cut a replica of the crown out of stainless steel. Two surface data acquisition approaches were investigated: a three-view measurement and a two-view measurement.

Calibration of the Solid Photography equipment showed it to be capable of measuring surfaces within a cubic volume 0.5 inch on a side to an average error of ±0.001 inch plus a random error of ±0.001 inch around the local average values. Registration of data taken in each of two views was generally within ±0.004 inch. The wax crown pattern and plastic tooth post were very thinly coated with white paint to produce a satisfactory reflective surface for optical measurement. A crown of satisfactory detail and accuracy was milled out of stainless steel from the data base measured from three views.

Three-view processing was more easily accomplished but requires the extra cost of processing the third view. Based on preliminary results obtained in this study, it is believed that a satisfactory procedure can be used for replication of a crown from two views and it is recommended that this principle be used for lowest cost replication.

A steeper milling angle will be required for the interior cut to assure access to interior side surfaces. Modificiation of the measurement system configuration is recommended as described within this report to enable measurement of the two sides not in view with the present equipment. Surface finish can be improved by developing smoothing functions. Going to a five-axis milling machine will enable automatic removal of residual material not accessible by a four-axis machine.

It is believed that ultimately Solid Photography can be adapted to obtain the data base for crowns directly from the surfaces in a patient's mouth. For now, feasibility of automated crown replication has been demonstrated and could be developed as a cost-effective alternative to conventional casting procedures.

FOREWORD

Solid Photography^{SM} provides an economical approach to obtaining the large digital data base necessary to describe a complex surface. This data base is required when a numerically-controlled machine is used to replicate the surface out of a block of material. The desire to eliminate dependance on limited supplies of castable strategic materials and the ever-present need to reduce the cost and time to produce a crown leads inevitably to the use of direct machining. This study has shown that it is feasible to use Solid Photography to generate the digital data base from a wax pattern and post. The data accuracy is on the order of ±0.002 inch which is considered to be satisfactory.

It was found that an opaque, diffuse reflective surface was necessary for high quality measurement. Surfaces not measurable by the present equipment can be measured by modification of the system. Similarly, modification of the data processing and addition of another axis to the milling machine will provide a system capable of producing excellent quality crowns on an economical basis.

1.0 INTRODUCTION

Crowns are presently cast from expensive, strategic materials. The casting process is labor intensive and automation could potentially lower production costs. Numerically-controlled machines could directly replicate a crown from suitable non-strategic and low-cost materials which possess desireable hardness and non-corrosive properties. The key problem confronting this approach has been the inability to obtain the three-dimensional digital data base describing the crown surface rapidly and economically. The crown surface is not easily described by mathematical functions that computers could convert into machine orders. Since each tooth is different, a customized approach was necessary for acquiring the surface data for each one. A rapid, accurate surface measurement system was required.

This feasibility study was initiated to determine whether a newly announced technology, Solid Photography, could be adapted to measure and directly replicate crown patterns accurately enough to eliminate the standard casting process for producing crowns. No attempt was made to modify the existing experimental Solid Photography equipment known to be capable of measuring objects the size of a dental crown with a 0.001-inch resolution. However, careful calibration of the equipment was necessary to attain the accuracy required for crown replication. An accurate holding fixture was required to enable the measurements taken from various angles to be joined together with little relative error. Surface reflectance of the crown and tooth post had to be modified to enable photographic recording of the surface measurements. Software procedures had to be developed to invert the exterior tooth post measurements to form the crown interior. A physical support had to be added by software to hold the crown while surrounding material was stripped away. Finally, special tools had to be made to cut the stainless steel from which the crown was to be carved. Further development in machining methods should provide economic benefit.

This report provides some background on Solid Photography, a description of the steps followed in acquiring and processing the data, and a summary of machining considerations. The positive results of the study demonstrated the feasibility of the Solid Photography process in the replication of dental crowns.

2.0 BACKGROUND

A new technology for rapid generation of digital data bases representative of surface locations was announced by the Company in June 1976. In a process called Solid Photography a person sits in the center of a studio with eight cameras aimed at him from various angles to view all surfaces of his head. Then four projectors illuminate him and the cameras record the light patterns cast by the projectors. After developing the film, the film is read by an automatic film reader which generates digital numbers representative of the patterns on the film. A digital computer then interprets these numbers as surface measurements which a numerically-controlled milling machine is programmed to follow. The result produces amazingly accurate and low-cost portrait sculptures.

At the same time that Solid Photography portrait sculpture was announced, the Company announced that experimental Macro and Micro Studios were also in existence based on the same technology. The Macro Studio showed that it was possible to scale the measurement volume up in size, with resolution proportional to size. One subject of the Macro Studio that was demonstrated was the front of a Volkswagen car measured with a resolution of 0.3 inch. The Micro Studio showed that as the measurement volume was scaled down, resolution was retained. A grasshopper's head was measured with a resolution of 0.001 inch.

3.0 DATA ACQUISITION

The three-dimensional data for the crown were obtained in the Solid Photography Inc. experimental Micro Studio version of the three-dimensional replication process. The Micro Studio consists of a projector, two cameras and a mounting fixture to hold the object to be replicated. Figure 1 is a photograph showing the crown and post mounted in position. Also seen in the photograph are the

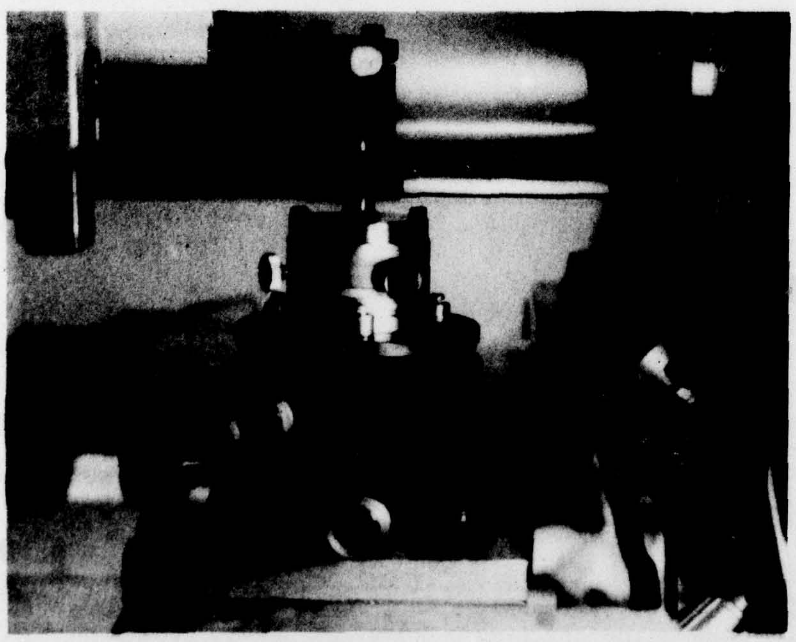

Figure 1. Crown and Post Mounted in Position

projection lens and one (lower) camera lens. Three-dimensional data are acquired through a process of projecting and photographing a series of light patterns on the object. Each camera acquires three-dimensional data within its field of view. Several cameras and projectors are required to adequately cover a typical three-dimensional object if all surfaces must be measured simultaneously. When inanimate objects are copied by the Micro Studio, the full field coverage may, however, be implemented by re-orienting the object in front of a fewer number of cameras and taking a succession of measurements. In the Micro Studio one projector and two cameras are used. These cameras are at ±45° from the projector optical axis. To obtain sufficient data for the crown replication, three views were measured by rotating the crown ±90° in addition to the first position. Rotational accuracy was ±0.25 degree. These three views were used to generate the outside surface of the crown.

Since the inside of the crown matches the post, three-dimensional data on the post can be used (with suitable software inversions) to generate the inside of the crown; hence, three views of the post were also measured.

3.1 Measurement Procedure

The procedure can be explained with the aid of figures 2A and 2B.

1. The post was mounted in the fixture as shown. In general, the position of the tooth is not critical as long as it is within the viewing volume (0.5-inch cube). However, when using this three-view procedure, some care must be taken in mounting the post such that the sides of the post are aligned symmetrically with respect to the optical axis. This is to insure that the taper of the sides of the post match the tool taper angle of the cutting tool. A gross misalignment of this angle would require additional processing and cutting.

2. A sequence of pictures was taken with each camera at this angle (reference 0°).

3. The rotational stage (see figure 1) was then rotated +90° and a sequence taken.

4. The rotational stage was then rotated −90° (from 0°) and a sequence taken.

5. The crown was next placed on the post and the three sets of picture sequences repeated.

6. The film was unloaded from the cameras, developed, spliced together in proper order and turned over for reading and processing.

3.2 Data Acquisition Problems

Two problems were present in the tooth data acquisition; one photographic, the other mechanical alignment.

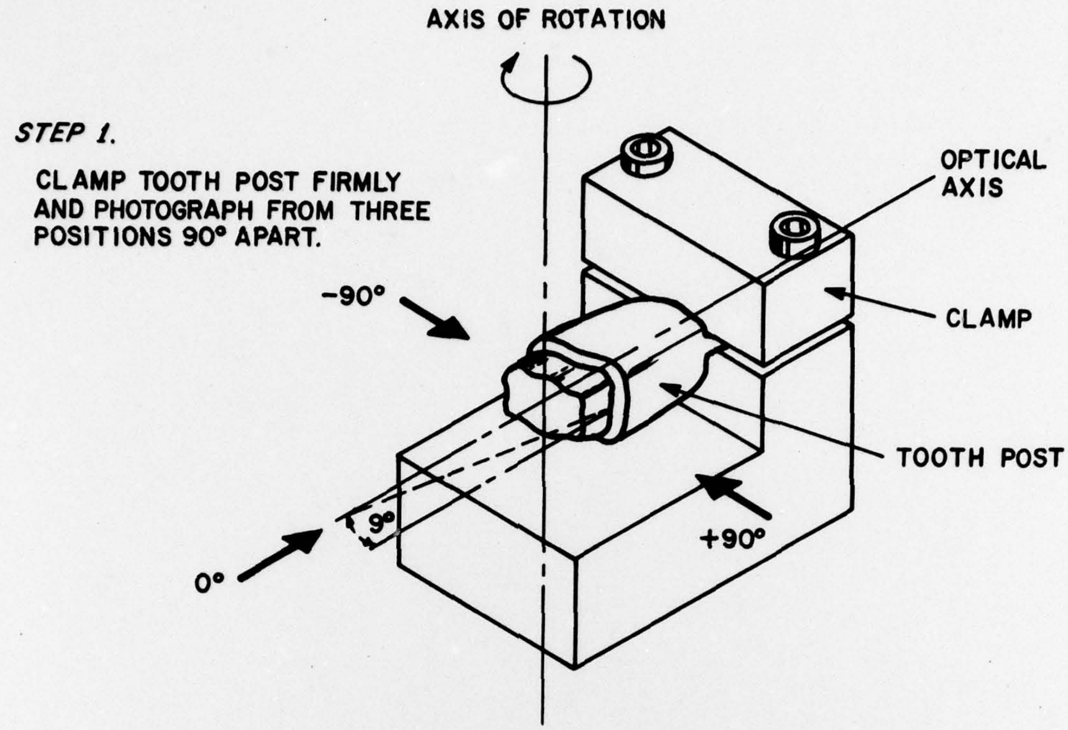

Figure 2A. Tooth Post in Measurement Fixture

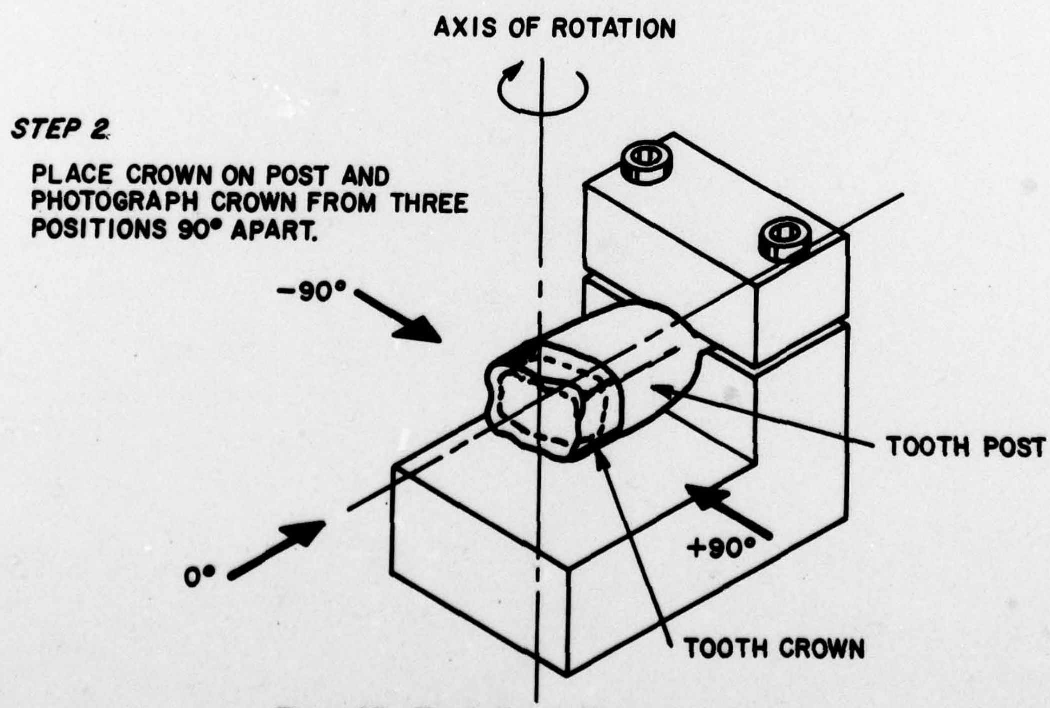

Figure 2B. Tooth Crown Mounted on Post

A matte diffuse surface is most ideal for photographic reproduction of the projected light patterns. Specular (mirror-like or shiny) surfaces may introduce spurious reflections. Translucent surfaces scatter light from within the volume and obliterate the surface reflection. Examination of the tooth showed that both the post and crown were translucent in addition to having specular components of the smooth surfaces. Trial photographs of the tooth confirmed that the data was washed out from internal scattering of the translucent material. Some surface preparation was necessary. Best results were achieved with sprayed-on flat white acrylic paint. Tests indicate that the thickness of the paint is approximately 0.00075 inch with surface irregularities on the order of 0.0002 inch. Both crown and post were suitably painted. In order that removal of the crown not remove paint from the post, the post data were taken first as outlined above.

The second problem has to do with the mechanical alignment of the rotational axis with respect to the computer-based rotational axis. In the initial setup of the experimental Micro Studio an elaborate procedure was used to determine the relative positions of the projector and camera axes and their point of intersection. This established a computer-based rotational axis. Over the course of time the initial real rotational axis and the computer axis drifted slightly from one another. These drift errors caused discontinuities in the data. Computer processing was used to smooth over the discontinuities. This computer smoothing did not detract from the aesthetics of the replication of previous subjects copied by the Micro Studio. However, in order to make the crown fit the post greater absolute accuracy was required. To this end a means was devised to realign the two axes.

A precise 0.5-inch cube was fabricated, painted and installed in the tooth fixturing. 0°, ±90° photo sequences were then taken and the output data compared to the physical size and position of the cube. Errors in tilt and the position of the axis were indicated. Using 0.0001-inch reading dial indicators and a microscope with 0.00025-inch graduation the rotational axis was adjusted to the computer determined position. (See figure 1 for a picture of the tilt and rotational adjustments.) The cube was then rephotographed and touch-up adjustments were made.

After these axis corrections the final post and crown data acquisition sequences were made.

3.3 Alternate Method

Since it was felt that taking the data from three positions might be an approach that was too conservative, a two-view measurement was made at the same time and processed separately. The post and crown were positioned halfway between the front and right side views and photographed. The post and crown were then rotated 90° to expose the surfaces between the left side and front view.

An additional advantage of using just two views instead of three over the obvious reduction in measurement and processing times is its application toward the ultimate goal of photographing post and crown information in the patient's mouth. It is vital to minimize the number of views in the mouth to keep the instrument size small, keep costs low, and keep the measurement time and effort minimal.

3.4 **Conclusions**

The three-dimensional replication process in the present equipment gathers no depth information from any surface which lies in a horizontal plane. In the replication performed under this contract the tooth was rotated on a vertical axis. Hence, surfaces which were approaching horizontal in one view were approaching horizontal in all views. Thus, the top and bottom of the crown contain noisy depth data. It should be pointed out that this is strictly a limitation of the experimental equipment used. If additional views were taken with a rotation of the tooth such that the top and bottom were rotated to the sides as shown on figure 3 this problem would be alleviated. However, this would have required additional costs beyond the scope of this study. It is recommended, further, that the alternate method described in section 3.3 be used in order to decrease the time required for data acquisition, processing and replication. A preliminary investigation indicates that four single camera views each on the post and crown would provide all the data required. The post would be mounted as shown in figure 3. The camera and projector would obtain measurements on each of the four sides with the front surface.

Fixturing would be desired specifically for post-crown data acquisition. Stops would be used to locate angles repeatably rather than vernier scale readings. Increased use of automation would be employed to minimize operator error.

4.0 DATA PROCESSING

In order to process the Micro Studio data obtained on the crown and post with accuracy on the order of ±0.001 inch it was necessary to perform the following tasks:

- Calibrate measurement volume
- Provide correction data for mechanical placement of the Micro Studio mounting fixture
- Merge crown data with reversed post data
- Generate cutting tape with tool offset

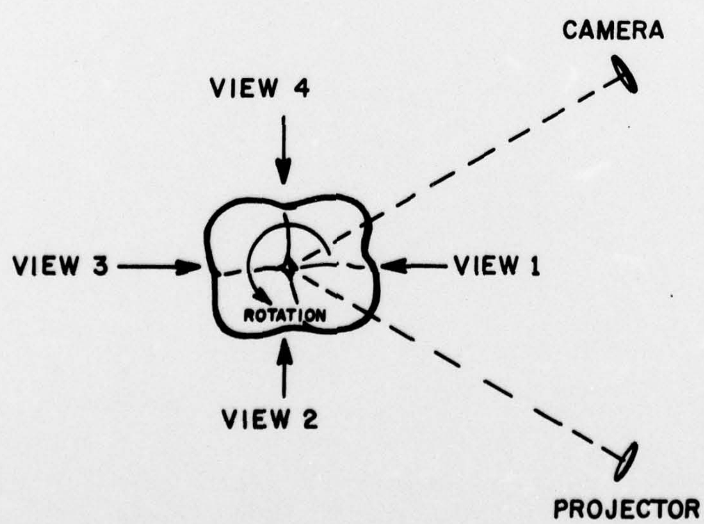

Figure 3. Recommended Measurement Configuration

4.1 Calibration

A 0.500-inch metal square, painted white, was used to verify the system measurement accuracy. After painting, the square measured 0.5014 inch. Assuming the paint coating on the post and crown would be of comparable thickness, all calibrations assumed the square to be 0.500 inch. In this way the system should tend to compensate for the paint thickness on the post and crown.

The square was placed in three locations and measured. The square was placed at the front of the viewing volume, then at the center and finally at the rear. The average differences measured between the known physical locations and those reported by the Micro Studio ranged from +0.002 to −0.005 in the x dimension (forward-aft), +0.007 to −0.006 in the y dimension (left-right), and +0.0017 to −0.0018 in the z dimension (up-down). A computer program was written to reduce these averaged errors to ±0.001 in most cases. In addition to average errors, random errors occur. For most of the data these additional errors were no greater than ±0.001. Two cameras were used to record data, a camera above and one below the subject. Both simultaneously measured the same surface only from different angles. The above errors were for both cameras individually; averaging the data together, as is done in the processing to produce a final data file further reduces the errors in the file.

4.2 Mechanical Corrections

A 0.500-inch metal cube, also painted white, was used to assure correct merging of data as the subject was rotated ±90° to expose the right and left sides to the cameras after measuring the front of the cube. After painting, the cube measured 0.502 inch wide and 0.501 inch high, so the assumed uniform paint thickness seemed well founded. By noting measured non-parallelism of edges known to be parallel between the right and left cube sides, it was possible to readjust the rotational axis to be parallel to the vertical axis of the measurement volume. Subsequent measurements showed parallel edges to be measured as parallel. By noting displacement of cube sides as measured relative to their correct relationship it was possible to determine how much the rotational axis was displaced from the center of the measurement volume. A correction was made for this displacement and verified by subsequent measurements.

4.3 Merge Crown and Post Data

The crown and post were coated with white paint assumed to be of a thickness comparable to that used in calibration so that compensation would occur automatically. First, the post was mounted horizontally to measure the front and two sides. The crown was then placed on the post and its front and two side surfaces measured. The two data sets were processed independently then the post data was converted from a convex surface to a concave surface by, in effect, viewing the data from the opposite side. That is, data measured from the front were treated as if measured from the rear. This data supplied one quadrant of the final data. The other three quadrants were taken from the crown data.

A critical check of the data accuracy was possible at this point. The relative positions of the post and crown data sets, where they met at the outer rim of the crown edge, were found to agree within 0.004 inch on a horizontal cut across the center. Both sides gave data that appeared to be shifted 0.004 inch toward the crown front. One side also appeared to be 0.003 inch toward the crown center. This results in cutting away 0.004 inch too much material from the outer side of the crown near the lip

producing a slightly undersized lip on that side. After undercutting, the residual thickness of the lip was 0.025 inch which was equal to the lip thickness on the other side where no undercutting was obtained.

An interesting measurement occurred when a 0.006-inch crack between the crown and post was measured. The crack was 0.030 inch deep and the two central of six measurement points correctly reported this depth. No data were obtained in the two measurement points on either side of the two reporting points. The crack was in the vertical direction, thus giving line of sight access to the cameras. This demonstrated the system's ability to obtain measurements in very confined areas.

The final processing operation added a data set representative of a mechanical support on the bottom of the crown to provide physical support when machining. Since the crown was photographed on its side, it was cut on its side with this mathematically-generated support under one side to hold the crown in place as the surrounding material was cut away. Undercutting by 0.020 inch in front and rear left a residual support of 0.146 inch. Undercutting by 0.050 inch on each side left a residual width to the support of 0.300 inch. These dimensions were chosen as adequate for the mechanical stresses anticipated during cutting.

4.4 Generate Cutting Tape

The measured surface data were modified to produce a cutting tape containing a three-dimensional locus of points shifted three dimensionally by an amount such that the surface of the cutter (ball end mill of 0.020-inch diameter) coincided with the original data. The data, because of its digital form, represents the surface as discrete changes in depth to be cut by the machine tool. The smallest end mill tool obtainable had a 0.010-inch radius. The tool offset program, therefore, considered where the tip of the tool should be positioned to avoid cutting into the desired surface locations. The relatively large radius therefore must leave a small amount of excess material in interior corners having effective radii less than 0.010 inch. Except for tool taper, exterior surfaces could be milled without leaving any excess material. The computer program automatically added the correct offset values to the measured surface coordinates and recorded the modified values on a magnetic tape to drive the numerically-controlled replicator.

4.5 Alternate Method

The same processing procedures were used to obtain a data base from just two viewing positions 90° apart. A new problem was encountered as a result of capturing data behind the post lip as shown in figure 4. When the data on the post surface were measured in a front view, the lip shadowed the data to the rear. When the data were reversed to obtain the internal crown surface no data existed in front of the lip. This was not the case when viewed 45° from the front since the lip no longer shadowed the rear part of the post. This data became foreground data when the data were reversed to obtain the crown's internal surface. This unwanted data then required a new removal procedure since no software existed to automatically remove it. This was partially accomplished by removing all data more than 0.030 inch in front of the crown lip. The tool was only able to demonstrate the effectiveness of this procedure near the central side area due to the limited software effort. Further effort should satisfactorily resolve this problem.

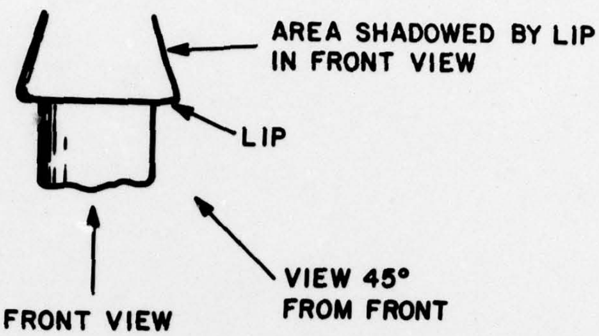

Figure 4. Top View of Post Measurement

Another problem appeared when cutting the inverse post. The problem encountered was due to the physical orientation of the post. The tool could not cut the entire inside surface as illustrated in figure 5.

A solution to this could be to change the ±45° viewing angles to ±22½° or some other value greater than the tool taper angle of 9°. By rotating these two views the cutter limit would be moved closer to the sidewalls as shown in figure 6. This method would allow for more than enough of the required tool overlap.

This could be accomplished by either rotating the tooth post mechanically before the pictures are taken or by rotating the data by computer software.

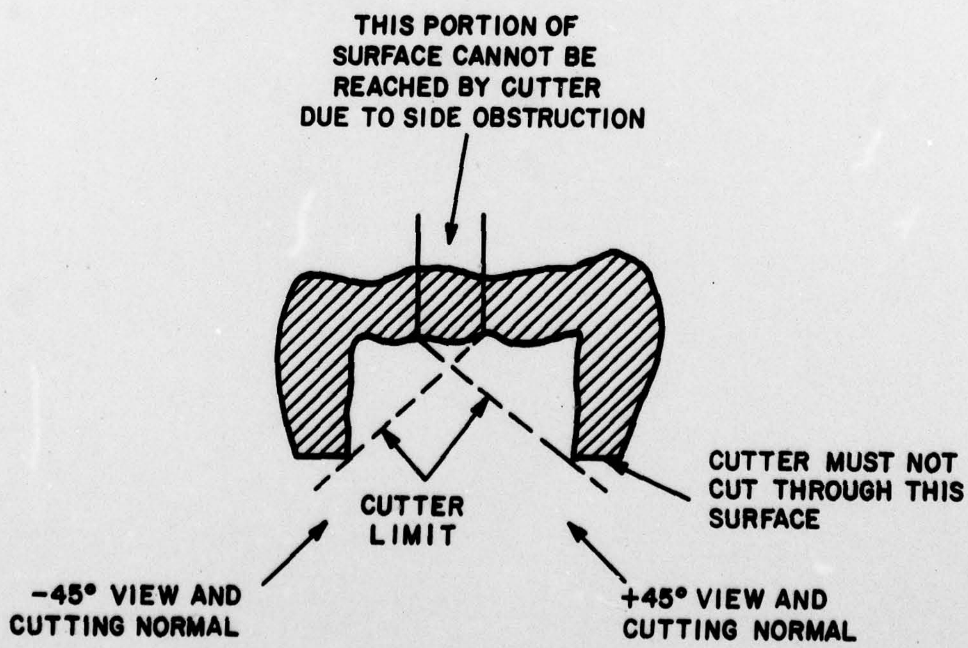

Figure 5. Top Cutaway View of Crown

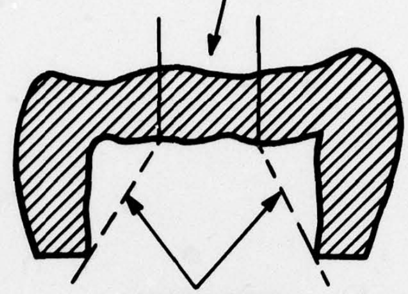

Figure 6. Top Cutaway View of Crown

5.0 FABRICATION PROCESS

In order to machine a tooth crown from a solid block of stainless steel within a machining accuracy of ±0.001 inch, the following tasks had to be performed:

1. Cutting tool design and fabrication.
2. Mounting fixture design and fabrication.
3. Tooth crown material selection.
4. Machine 1/1 scale plastic replica of tooth crown.
5. Machine 1/1 scale stainless steel replica of tooth crown.

5.1 Cutting Tool

One of the cutting tools designed to cut the tooth crown from a solid block of stainless steel was fabricated from a solid bar of micro-grain carbide. The tool is basically a 7° taper (14° including angle) ball end mill with end cutting capability. The front end is three fluted and 0.020 inch in diameter. The back end is 18 fluted and 0.265 inch in diameter. The 18 flutes generated at the back end of the cutting tool are tucked in around the helix angle until the front end is reached with three flutes. This provides for smoother cutting action during side cutting and eliminates vibration which is detrimental to extremely hard materials such as carbide. The tool concentricity is critical over its 1.500-inch length to not only eliminate vibration but to also maintain cutting accuracy. The cutting tool was designed to machine the tooth crown form in a single pass per quadrant since it was felt that a roughing cut followed by a finish cut would not be cost effective in terms of machine time. It was found however, that during a pass which consisted of long plunge cuts the cutting tool did not have enough strength at the front end to prevent walking of the tool tip and subsequent breakage.

A 3° taper die sinking cutter fabricated from solid carbide with a tip diameter of 0.062 inch was then used to rough out the tooth crown form to 0.125 inch of the final surface. This cutter had the required strength to withstand the deep plunge cuts of the tooth crown form.

5.2 Mounting Fixture

The mounting fixture consisted of a cylindrical chuck to hold the stainless steel blank which was in turn mounted to a 10.00-inch diameter precision indexing head. The positional index accuracy from station to station is within ±0.0002 inch at the rim and repeatable within 0.001 inch non-cumulative. The concentricity on indexing is within ±0.001 inch TIR at the spindle drive shaft. The flatness on indexing is ±0.001 inch TIR for 360°. The indexing head was mounted to a 3-axis N.C. milling machine to provide a total of four axes of movement.

5.3 Material Selection

The material selected to demonstrate machining capability was stainless steel type 303 (QQ-S-764) MIL–W–52263. The basis of the selection was made on machinability, availability and material cost. Stainless 303 is free machining and can be ground and polished satisfactorily.

5.4 Machining of Plastic Replica

The machining of the plastic replica (material: cast acrylic) at 1/1 scale was done to quickly check the machining data and camera merging.

The cutting was accomplished with a cobalt steel 9° taper single flute profiling tool with a tip diameter of 0.020 inch. The plastic replica was cut at a spindle speed of 12.000 RPM with an approximate feed rate of 0.125 inch/second.

The tooth post did not have the required 9° taper angle for tool clearance on the inside surfaces of the tooth crown. Therefore, an interference fit existed between the tooth crown and the tooth post. The tooth post side surfaces were hand-scraped to an approximate 9° taper angle to enable checking the fit of the tooth crown lip to its mating surface on the tooth post.

5.5 Machining of Stainless Steel Replica

The machining of the stainless steel (type 303) replica at 1/1 scale was done with a high-frequency, vacuum-cooled, 1.5 H.P. power quill with a speed range of 4,000 to 40,000 RPM rigidly mounted to the ram bracket of a 4-axis N.C. milling machine.

A water soluble coolant/lubricant was applied as a vapor mist during the machining operation to prevent tool loading and heat buildup.

The die sinking cutter used for the rough cut operation at a single pass per quadrant cut well with a good surface finish at a spindle speed of 40,000 RPM and an approximate feed rate of 0.050 inch/second.

After the rough cut the tooth crown had 0.125 inch of material to be removed for a finish cut to the final surface.

During the finish cut operation at 40,000 RPM and approximate feed rate of 0.050 inch/second with the 0.020-inch diameter finishing cutter there was tool breakage on deep plunge cuts. It was determined that the cutter was speed-limited and could not remove material fast enough and several passes per quadrant were required. It is felt that by using a higher spindle speed (approximately 75,000 RPM) it would have been possible to remove the remaining 0.125 inch of material in a single pass per quadrant.

The stainless steel crown, still attached to the steel stock, is shown in figure 7. Air gaps at the interface with the lip of the post were less than 0.003 inch except in a few locations where localized gaps of up to 0.005 inch occured. Figure 8 shows an enlarged view of the interface.

6.0 CONCLUSIONS

The feasibility of automated tooth crown replication has been demonstrated by this study effort. Measurement accuracy on the order of ±0.002 inch has been achieved. Automatic processing from measurement to the generation of a magnetic tape with the machine cutting orders is possible and has in fact been accomplished with minimal operator assistance to call the various processing programs. A steel replica of a wax crown pattern was milled from stainless stock. Although the milling process was quite lengthy, improvement in this area is not expected to be difficult.

The experimental measuring Micro Studio equipment used was not intended for the specific task of measuring crowns nor for accurate measurement. However, it was found to be quite close to fulfilling the requirements, so that a system using essentially the same design with a modified holding mechanism should provide the desired performance. This is a new technology and many avenues of improvement exist. A solid-state sensor could replace the film. Hardware data processing can reduce the processing time as can special purpose programming for crown replication. Direct machining of all surfaces appears possible as does improved surface finish. Faster machining, which is achievable, should make the process economically attractive.

7.0 RECOMMENDATIONS

On the basis of this study it is recommended that a system designed specifically for automatic crown replication be developed using Solid Photography, specialized software, and a specialized replication machine. The measurement sequence should be automated to eliminate human error, and provide a high throughput rate. The same recommendation applies to processing and machining. Preformed metal blanks should enable the maximum machining rate to be achieved.

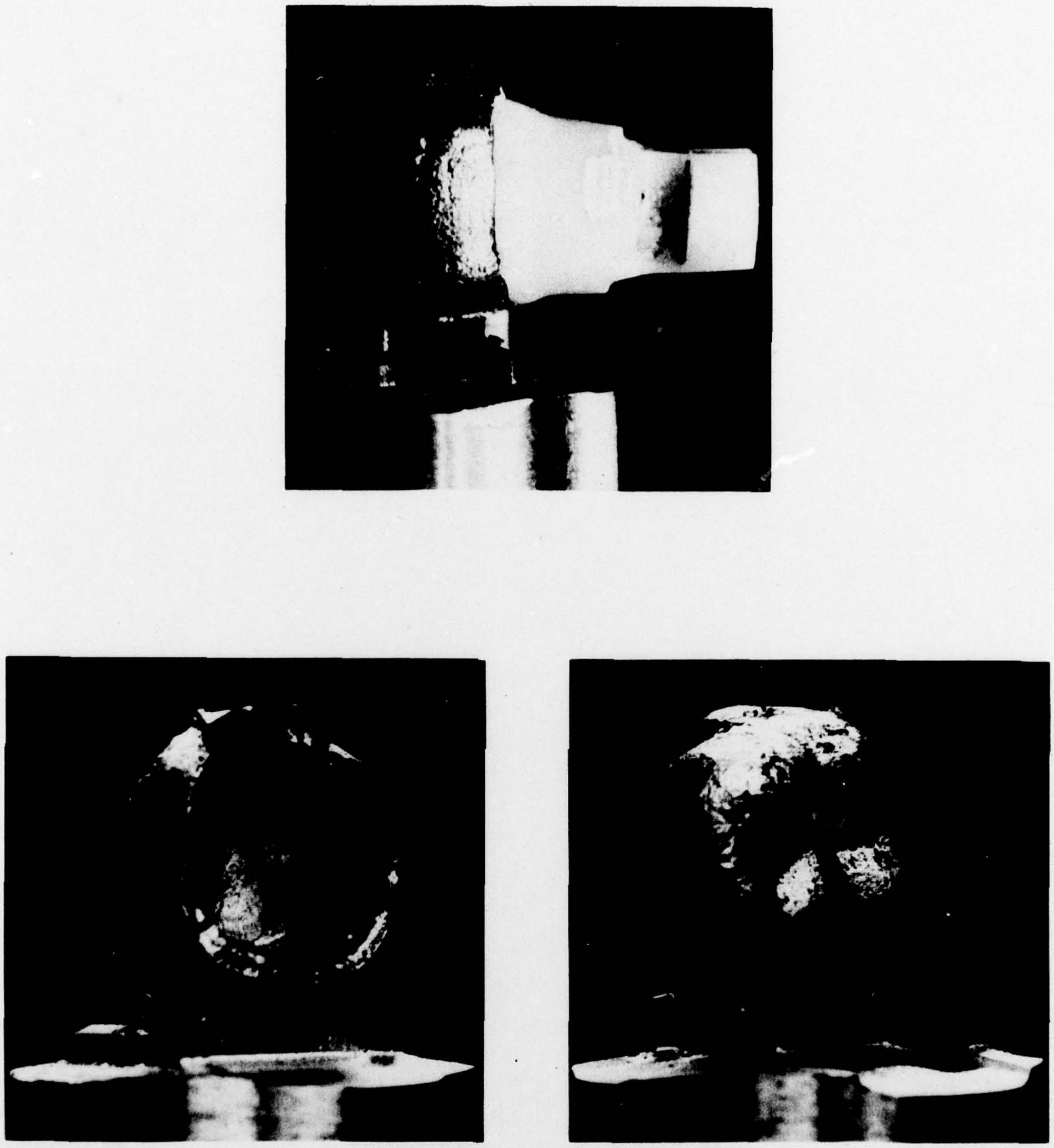

Figure 7. Replicated Crown

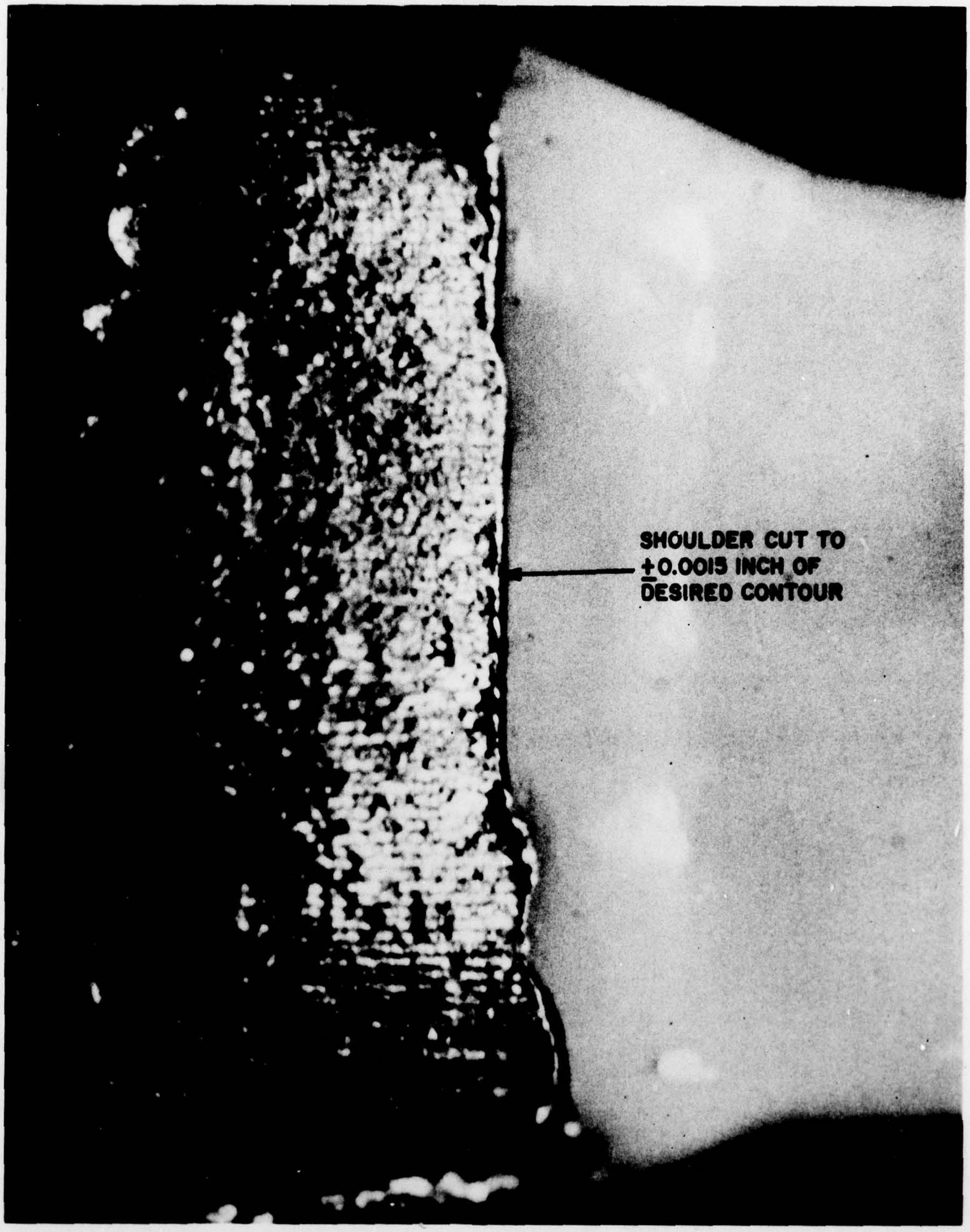

Figure 8. Enlarged View of Crown Lip (Shoulder)
Scale: 0.050" per inch

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